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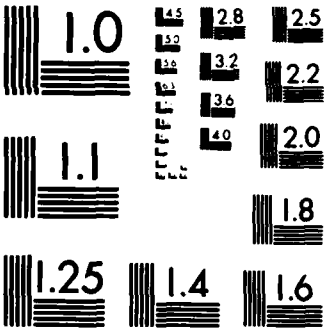

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The objective of this work ~~is to~~ significantly advance the understanding of electromagnetic interactions with small particles whose dimensions are of the order of a wavelength. A joint theoretical-experimental approach is used so that theoretical predictions could be provided with experimental back-up and vice-versa. Extensive results on electromagnetic interactions with cubes and sphere multiplets have been obtained. Beautiful symmetry theorems for forward and backward scattering have been discovered. A major theoretical bonus has been the formulation -

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Measurement and Calculation of the Stokes or Mueller Matrix for the Scattering of Electromagnetic Radiation from Irregular Particles

Final Report

Edward S. Fry, Chia-Ren Hu, and George W. Kattawar

August 11, 1986

U.S. ARMY RESEARCH OFFICE

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TEXAS A&M UNIVERSITY

Introduction

The objective of this work is to significantly advance the understanding of electromagnetic interactions with small particles whose dimensions are of the order of a wavelength. A joint theoretical-experimental approach is used so that theoretical predictions could be provided with experimental back-up and vice-versa. Extensive results on electromagnetic interactions with cubes and sphere multiplets have been obtained. Beautiful symmetry theorems for forward and backward scattering have been discovered. A major theoretical bonus has been the formulation of a new and very efficient method for obtaining electromagnetic scattering properties of an arbitrarily shaped particle which is built from smaller particles whose scattering has been determined. Brief summaries of important results are given in the following sections. All of them have been published or are in the process of being published.

Cubes

1. We have successfully developed a large set of computer programs to calculate the complete Mueller matrix for a cube in a fixed orientation or in random orientations. The programs are based on the resolvent kernel theory which we have worked out. The method is extremely powerful since the kernel is independent of the incident field and *only* depends on the nature of the scatterer. Consequently, once the kernel has been obtained, the scattering by a cube in any orientation in the incident beam is very simple to obtain. We have compared our calculations with experimental observations with very good success. A paper describing the technique has been accepted for publication in Applied Optics.

2. A major experimental success was the development of a technique for holding single, micron-sized cubes in fixed orientation using radiation pressure. The technique makes it possible to manipulate and/or spin such particles. It is described in the Proceedings of the 1985 CRDC Conference on Obscuration and Aerosol Research and is preparation for Optics Letters.

3. Mueller matrix measurements of the oriented cubes have shown that a cube makes abrupt shifts between stable orientations over time intervals of about 4 to 5 seconds.
4. Ray tracing calculations have provided a physical picture of the orientation forces and torques on a cube. These results will appear in the 1986 Proceedings of the CRDC Conference on Obscuration and Aerosol Research.

Cooperative Scattering

The cooperative scattering segment of our program has accomplished the following:

1. Modifications to the existing two-sphere program were made that allowed easy comparison between the scattering properties of a bisphere and those of two noninteracting spheres.
2. The program was then extended so that the scattered fields in the near zone, including the fields on the surface of the bisphere, could also be investigated. One of the first topics considered in this area was the behavior of the radial component of the Poynting vector of the scattered radiation near a morphological resonance of the (independent) constituent spheres.
3. The results of some of our studies of the Mueller matrix of a bisphere and of the radial component of the Poynting vector, as well as comparisons between exact calculations and certain approximations were presented at the 1985 CRDC Conference on Obscuration and Aerosol Research.
4. An article co-written with Prof. R.T. Wang of the Space Astronomy Laboratory of the University of Florida, and entitled "Electromagnetic scattering from two dielectric spheres: further comparisons between theory and experiment" has been published in the Aug. 1, 1986 issue of Applied Optics. In this paper, experimental measurements of the scattering properties of two-sphere systems were found to be in good agreement with theoretical predictions. The dependence of the strength of the correlation effects on particle orientation were also considered as were the effects of orientation on selected elements of the Mueller matrix.

5. The multiple scattering approximation of Bruning and Lo was refined in order to more accurately account for the proximity of the spheres to one another. This led to (at times dramatically) improved approximations of the backscattering cross sections of bispherical particles, and is also useful in the study of the range and behavior of the correlation effects mentioned earlier.

6. Approximate analytic expressions for the enhancement of Raman scattering by the presence of two small Ag spheres have been obtained, and a subsequent survey of the optical properties of various metals, semiconductors, and insulators has turned up a number of candidates which may be more effective than Ag at producing such enhancements. In connection with this work a paper entitled "Surface-Enhanced Raman Scattering by Two Interacting Spheres" was presented to the Joint Meeting of the Texas Sections of the APS/AAPT on November 8, 1985.

7. The expansion coefficients of the internal fields of either component of the bisphere have been obtained. This of course allows us to study all scattering phenomena of interest at points lying either inside or outside of the two-sphere system.

8. The computer program was modified so that light scattering by linear chains of an arbitrary number of spheres could be studied.

9. Probably the most important development has been the derivation of an alternative method for studying the physics of multiple scattering. This new method provides more information on the physics of cooperative scattering than was previously available, and it is often less expensive to use.

10. Two presentations of our results were given at the 1986 CRDEC Conference on Obscuration and Aerosol Research: A 15 minute talk outlining the new method, and a poster presentation that provided extensive comparisons between theoretical and experimental studies of EM scattering by linear chains of three and five spheres. The experimental data were kindly provided by Dr. Ru T. Wang (see 4.)

11. An article that deals with the topics described in 10) is in preparation for submission

to Optics Letters.

12. An article dealing with our studies of SERS from bispheres is in preparation for submission to the Communications section of JOSA B.

Symmetry Theorems for Forward and Backward Scattering

We have developed a *complete* set of symmetry relations for the forward and backward scattering of radiation from an irregular particle. These relations will very beneficial in categorizing particle shape. A paper on this subject has already been accepted for publication in Appled Optics.

Diffraction Theory

We have developed a numerical method to solve the Kirchhoff diffraction integral for a Gaussian beam in the near zone without approximation. This program is a general purpose one which can also handle integrals of highly oscillatory functions. This program was the sine qua non for understanding the orientational effects of various occulting shapes on a levitated cube.

Numerical Techniques

We have explored various sophisticated discretization techniques to improve the accuracy of the resolvent kernel method. We feel that we now have a method which is quite reliable and easy to implement for more exotic shaped objects. We have also developed a highly efficient program to calculate the resolvent kernel for a complex object using the kernels of simpler objects. This gives us the capability to calculate the scattering properties of virtually any object.

Publications

1. Chia-Ren Hu, George W. Kattawar, and Mark E. Parkin," Complete Mueller Matrix Calculations for Light Scattering from Dielectric Cubes of Dimensions of the Order of a Wavelength", Proceedings of the 1984 Conference on Obscuration and Aerosol Research
2. Kirk A. Fuller and George W. Kattawar,"Near and Far Field Scattering from Two Interacting Spheres", Proceedings of the 1985 Conference on Obscuration and Aerosol Research
3. Edward S. Fry, Pascal Herb, and William E. White,"Orientation of One Micron Size Cubes Suspended in a Quadrupole Trap", Proceedings of the 1985 Conference on Obscuration and Aerosol Research
4. George W. Kattawar, Chia-Ren Hu, and Mark E. Parkin," Mueller Matrix Calculations for Dielectric Cubes: Comparison with Experiments", Proceedings of the 1985 Conference on Obscuration and Aerosol Research
4. Chia-Ren Hu, George W. Kattawar, Mark E. Parkin, and Pascal Herb,"Symmetry Theorems on the Forward and Backward Scattering Mueller Matrices for Light Scattering from a Nonspherical Dielectric Scatterer", Proceedings of the 1985 Conference on Obscuration and Aerosol Research
5. Kirk A. Fuller and George W. Kattawar,"Electromagnetic Scattering from Two Dielectric Spheres:Further Comparisons Between Theory and Experiment", Appl. Opt., **25**, 2521, (1986)

SCIENTIFIC PERSONNEL

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2. Dr. Chia-Ren Hu
3. Dr. George W. Kattawar

Postdoctoral Students

1. Dr. Glenn Bennett
2. Dr. Pascal Herb

Graduate Students

1. Kirk Fuller (will complete Ph.D. within year)
2. Xu Mei Gong (working towards Ph.D.)
3. Jim McGee
4. Mark Parkin (will complete M.S. within year)
5. Kelly Thieme(working towards Ph.D.)
6. Ken Voss(received Ph.D. in 1984)
7. William White(working towards Ph.D.)
8. Eric Yuen(working towards Ph.D.)

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